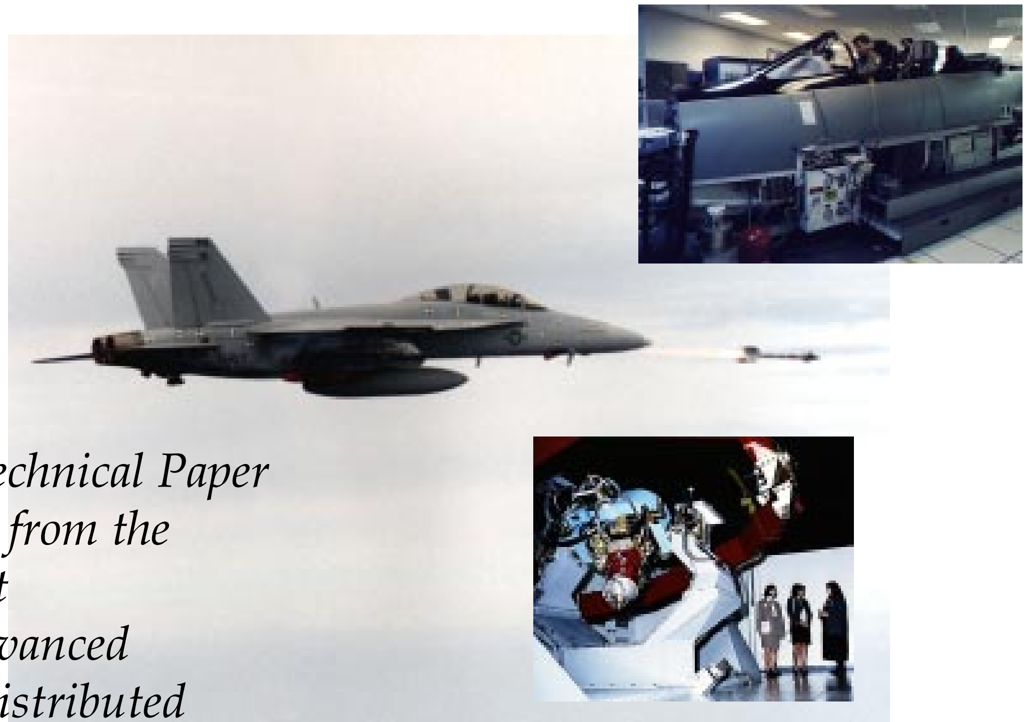
Verification and Validation of Distributed Air-to-Air Missile Tests



A Technical Paper
from the
***J**oint*
***A**dvanced*
***D**istributed*
***S**imulation*
Joint Test Force

Dr. Larry McKee, Science Applications International Corporation

Presented at the Simulation Interoperability Workshop
March 15-19, 1999

JADS JTF
http://www.jads.abq.com
11104 Menaul NE
Albuquerque, NM 87112-2454
(505) 846-1291
FAX (505) 846-0603

Verification and Validation of Distributed Air-to-Air Missile Tests

Dr. Larry McKee
Science Applications International Corporation
Joint Advanced Distributed Simulation Joint Test Force
11104 Menaul Blvd NE
Albuquerque NM 87112
(505) 846-0559
FAX: (505) 846-0603
mckee@jads.kirtland.af.mil

Keywords:
V&V, ADS, T&E, Distributed Testing

ABSTRACT: *The Systems Integration Test (SIT) was executed by the Joint Advanced Distributed Simulation (JADS) Joint Test Force (JTF) and evaluated the utility of using advanced distributed simulation (ADS) to support cost-effective testing of an integrated missile weapon/launch aircraft system in an operationally realistic scenario.*

The SIT scenarios simulated a single shooter aircraft launching an air-to-air missile against a single target aircraft. Extensive testing was performed involving two different ADS architectures: (1) the shooter and target were represented by manned flight laboratories and the missile by an AIM-9M Sidewinder hardware-in-the-loop (HWIL) laboratory and (2) the shooter and target were represented by live F-16 fighters and the missile by an AIM-120 Advanced Medium Range Air-to-Air Missile (AMRAAM) HWIL laboratory.

Testing was completed in October 1997, and evaluation of the results supports the conclusion that each ADS configuration has utility for test and evaluation (T&E) of the corresponding air-to-air missile involved.

The most important aspect of evaluating the utility of the ADS configurations was to demonstrate that valid T&E results were obtained for each missile system. The preferred method for evaluating the validity of the results was by replicating previous live fire testing profiles using the ADS configurations and showing that nearly identical missile results were obtained. Unfortunately, several complications prevented such a direct quantitative comparison.

This paper describes the modified verification and validation approach used during the SIT testing. This approach incorporated qualitative comparisons between the ADS results and the live fire results and quantitative comparisons between the ADS results and stand-alone HWIL results. The quantitative validation method involved first establishing the validity of the missile HWIL lab results in its stand-alone configuration and then using the stand-alone HWIL lab as a source of validation data for the linked results. Examples from SIT testing are used to illustrate the validation method.

1. Overview

The Joint Advanced Distributed Simulation (JADS) Joint Test and Evaluation program was chartered by the Office of the Secretary of Defense in October 1994 to investigate the utility of advanced distributed simulation (ADS) technologies for support of test and evaluation (T&E). The JADS Joint Test Force (JTF) is Air Force led with Army and Navy participation and is scheduled for completion in 1999. This paper discusses the verification and validation (V&V) approach used in the first of three separate JADS tests, the System Integration Test (SIT), which was completed in October 1997.

The SIT investigated the ability of ADS to support air-to-air missile testing. The test included two sequential phases, a Linked Simulators Phase (LSP) and a Live Fly Phase (LFP). Both phases incorporated one-versus-one scenarios based upon profiles flown during live test activities and limited target countermeasure capability.

The LSP distributed architecture is shown in Figure 1-1 and incorporated four nodes: the shooter, the F/A-18 WSSF manned avionics laboratory at China Lake, California; the target, the F-14 WSIC manned avionics laboratory at Point Mugu, California; the AIM-9M Sidewinder missile, the SIMLAB hardware-in-the-loop (HWIL) missile laboratory at China Lake; and a test control center initially located at the Point Mugu BMIC facility and later re-located in the JADS TCAC facility in Albuquerque, New Mexico. LSP testing was completed in November 1996, and results were documented in the final report for that phase (Ref. [1]) and other technical papers (Refs. [2] through [4]).

The LFP distributed architecture, shown in Figure 1-2, linked two live F-16 aircraft (a shooter and target) on the Eglin Air Force Base, Florida, Gulf Test Range; the Eglin Central Control Facility; an HWIL missile laboratory at Eglin which hosted an AIM-120 AMRAAM missile (the MISILAB); and a test monitoring center at the JADS TCAC facility in New Mexico. LFP testing was completed in October 1997, and results were documented in the final report for that phase (Ref. [5]) and other technical papers (Refs. [6] through [10]).

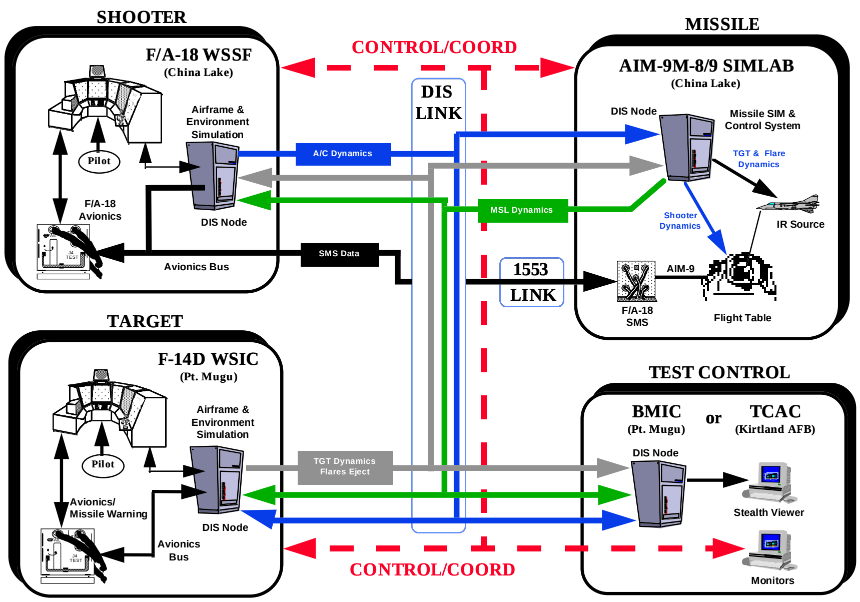


Figure 1-1. Linked Simulators Phase Test Configuration

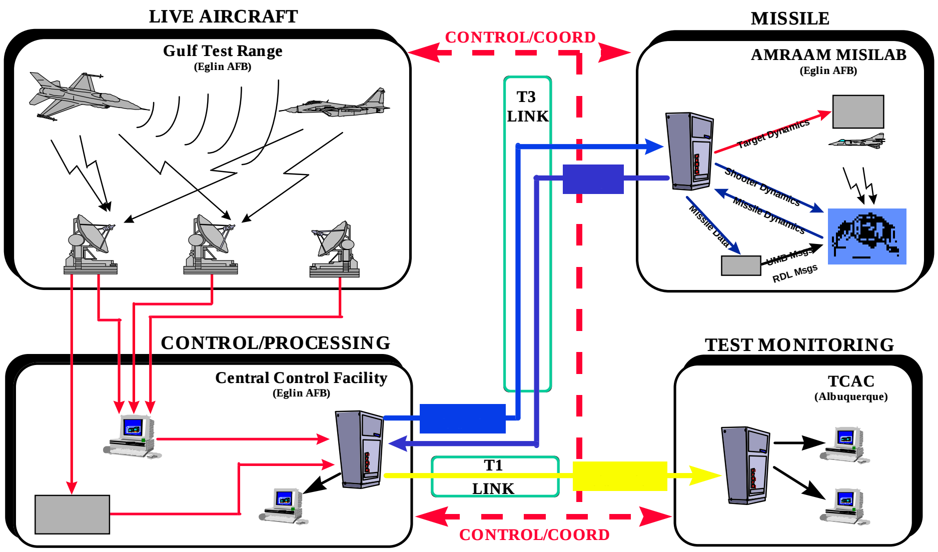


Figure 1-2. Live Fly Phase Test Configuration

A major objective of the SIT was to evaluate the validity of the missile performance data obtained using the ADS configurations. V&V methods were developed for this purpose which were consistent with those in the Verification, Validation and Accreditation (VV&A) Recommended Practices Guide (Ref. [11]), specifically bottom-up testing, functional testing, data integration testing, predictive validation, and comparison testing.

2. Verification

The missile HWIL simulations had been previously verified for their intended uses. Therefore, the distributed test verification was to confirm that the ADS configuration operated as designed when the nodes were real-time linked through an ADS network and could be used to replicate an actual live fire test, including the necessary data collection. Verification was an incremental and iterative process beginning pretest and continuing throughout the missions. The structured approach began with systematic check-out of each stand-alone simulator/ facility, followed by testing of each pair of linked nodes, and culminated with the check-out of the complete linked architecture, consistent with the bottom-up testing method in Reference 11.

2.1 SIT Verification Method

Data for verification were collected during integration testing and dry runs, in addition to data from executing the missions. Both qualitative and quantitative verification were performed.

Qualitative verification involved demonstrating that the shooter, target, and missile were properly linked by their behavior during linked testing, consistent with the functional testing method in Reference 11. This involved verifying the following:

- The shooter and target executed their respective profiles. This was determined from trajectory plots and from the quick-look readout of the launch conditions in the missile HWIL lab.
- The shooter acquired and tracked the target when both were represented by manned flight labs.
- The shooter provided proper prelaunch inputs to the missile in the HWIL simulation and launched it. This occurred when trigger squeeze by the shooter pilot resulted in initiation of the missile simulation.
- The missile in the HWIL lab responded to the target and any targeting messages from the shooter during its flyout:
    - The missile in the HWIL lab responded to targeting messages from the shooter by changing its trajectory.
    - The missile seeker tracked the target, as determined by missile experts monitoring the seeker telemetry channels.
- Quick-look missile telemetry channels in the missile HWIL lab were operating properly. This was verified by the lab operators.
- All data recording systems were operating properly. This was verified by reports from each recording location.

The quantitative verification involved checking the accuracy and timing of entity state and telemetry data passed between the nodes during linked runs, consistent with the data integration testing method in Reference 11.

- The input and output of each network interface unit (NIU) were compared to determine if the conversion of data formats and entity state coordinates occurred correctly. Differences between entity state values before and after coordinate transformations were computed and assessed to ensure that they were within acceptable tolerances.
- The timing of the transferred data was checked to ensure that their time dependence was not significantly distorted by sample-to-sample latency variations or by time stamp errors. Random latency variations can cause uncertainty in entity position if the data are not resynchronized at a receiving node (Refs. [2], [4], and [8]).
- The missile initialization and targeting messages generated by the shooter were checked at the missile HWIL interface to verify that correct timing was maintained between message components and that they were properly synchronized to the shooter and target entity state data.

2.2 SIT Verification Results

This approach successfully verified that facilities and entities were properly linked, that there were minimal errors in transforming entity state data, and that there were no protocol data unit (PDU) transmission errors. However, during LSP testing it was determined that random latency variations introduced uncertainty in the target position which could complicate evaluation of closed-loop interactions between the target and the missile (Ref. [4]). Also, a coordinate frame alignment error occurred in the SIMLAB during LSP testing (Ref. [2]); nevertheless, the response of the missile in the SIMLAB was valid for the target presentation it received.

3. Validation

The objective of the validation process was to demonstrate that the performance of the missile in the HWIL lab, driven by data from the aircraft, was consistent with that of an actual missile live fire profile under the same conditions.

3.1 SIT Validation Method

The preferred method for validation would be to replicate previous live fire test profiles using the ADS configuration and to directly compare results using quantitative techniques. However, several complications prevented this direct comparison:

- The live fire test data do not necessarily give a more accurate representation of the missile in the given scenarios. The live data were derived from range measurements and are subject to inaccuracies and uncertainties. Also, the live data represent only single realizations of the missile behavior for these scenarios. Multiple live shots using the same launch conditions and target trajectories would result in a slightly different missile flyout each time.
- The missile HWIL laboratory cannot perfectly simulate all aspects of the live missile behavior. Some differences were expected when the baseline runs were performed, even though the HWIL labs are validated and accredited missile simulations.
- The pilots cannot be expected to perfectly replicate the live fire profiles, and the shooter messages to the missile will not be identical.

These complications are illustrated with results from SIT testing below.

Because of these complications, the validation method employed used a multi-step process.

- The validity of the missile HWIL simulation itself was established by comparison to live fire data, consistent with the predictive validation method in Reference 11. Features of the comparison were as follows:
  - Twenty to twenty-five HWIL stand-alone (i.e., Monte Carlo (MC)) runs were performed with the same launch conditions and missile inputs as the live fire mission each time.
  - Distributions of the missile trajectories and key output signals versus time from the stand-alone runs were then compared to the live fire data.
- The validity of each SIT linked run was judged by missile experts based on a qualitative assessment of whether the missile HWIL simulation responded properly to the inputs received during the run.
- The validity of selected SIT linked runs was established by comparison to HWIL lab stand-alone runs, consistent with the comparison testing method in Reference 11. Features of these runs were as follows:
  - The shooter and target entity state data, along with the shooter messages to the missile, recorded during the live linked runs were replayed as missile HWIL simulation inputs during the stand-alone runs.
  - Twenty to twenty-five missile HWIL lab stand-alone runs were performed with the same inputs each time.
  - Distributions of the missile trajectories and key output signals versus time from the stand-alone runs were then compared to the data from the linked runs.
  - Note that in this case, the missile HWIL simulation was employed as a truth source for data comparison purposes, since it is a validated representation of the actual missile (as established in the first step above).

This approach compared statistical distributions of significant performance parameters, affording a higher level of confidence in the comparisons. Also, this technique allowed for the validation of profiles for which no live data existed.

3.2 Validation Examples

Examples of applying the validation methodology are given from SIT testing. These examples illustrate the complications of direct comparison to live data: live data inaccuracies, simulation performance differences, and pilot replication differences.

<u>Live Data Inaccuracies</u>. During the LFP, MISILAB (the AMRAAM HWIL lab at Eglin AFB, Fig. 1-1) stand-alone runs were performed which used the data from a live AMRAAM test (OP-612). The actual targeting messages

(messages generated by the shooter's fire control radar and passed to the missile either via the umbilical cable prior to launch or via data link after launch) were input into the MISILAB, along with the actual launch conditions. However, the time-space-position information (TSPI) data for the target from OP-612 had to be corrected in order to produce self-consistent results. The procedure for correcting the TSPI was to incrementally modify the target TSPI data input into an AMRAAM digital model until the model's missile telemetry output matched the data from the live OP-612 test. (The assumption for this process was that the missile telemetry data from the live test were more accurate and reliable than the range TSPI data; this assumption was supported by past experience with live fire test data.) The corrected target TSPI data were then input into the MISILAB simulation along with the other OP-612 data.

The results of the missile trajectories from the MISILAB stand-alone runs were used to determine envelopes of bounding values. The envelopes were then compared to the actual OP-612 TSPI data as shown in Figures 3.2-1a and 3.2-1b. These figures show the following:

- The MISILAB stand-alone runs which determine the envelopes are denoted by the MISILAB run number. Since the missile flyouts from the stand-alone runs often crossed each other, more than two runs were needed to determine all parts of the envelopes.
- The target trajectory input to the MISILAB simulation is denoted as "Target - MC Runs" in the figure. This trajectory was determined from the iterative digital model runs described above.
- The target trajectory from the OP-612 TSPI data is denoted as "Target - OP-612" in the figure. Note that there was a large discrepancy between the corrected target TSPI data and the raw data from OP-612, especially in the vertical direction. Figure 3.2-1b shows that the OP-612 TSPI data indicated that the missile did not intercept the target, but flew over 200 meters above it. However, the missile was observed to successfully intercept the target during the actual OP-612 test, as the corrected TSPI data show. These results are consistent with past observations that TSPI data determined from range tracking radars during live fire tests are subject to large bias errors, especially in the vertical, or elevation, direction. (Note that there were two separate sources of TSPI data for the target and missile, respectively, during OP-612. The missile TSPI data were determined from range tracking radar measurements, and the target TSPI data were determined by the drone control system. Hence, it was possible to have a bias between these two sources of TSPI data.)
- The envelope of trajectories from the MISILAB stand-alone runs had the same shape as the missile trajectory from the OP-612 TSPI data (denoted as "Missile - OP-612" in the figure), but was offset from it. This "offset" feature was consistent with the differences between the corrected target trajectory and the target trajectory from the OP-612 TSPI data, and the similarity in the missile trajectory shapes supported the conclusion that the MISILAB results were valid.
- The missile trajectories did not display the "single loft" shape seen in other MISILAB results. This was found to be due to the quality of the actual OP-612 data link targeting messages (some of the data link messages were erroneous). This result vividly illustrates the importance of the targeting messages in determining the missile trajectory and the difficulty in replicating missile behavior through replication of the live aircraft behavior (i.e., the missile behavior in OP-612 cannot be replicated without replicating the umbilical and data link messages, as well as the shooter and target trajectories).

The conclusion was that apparent errors in the OP-612 TSPI data prevented a direct comparison between the live test missile trajectory and the trajectories from the stand-alone runs. Such TSPI errors have been common in past live fire testing. A direct comparison was also complicated by the unlikelihood of replicating the targeting messages which play such a decisive role in determining the AMRAAM's trajectory.

Simulation Performance Differences. Data from the live AIM-9M test replicated during LSP testing (LPN-15) had been carefully smoothed during post-processing, so that the range TSPI agreed with observations of the missile intercept of the target (i.e., biases and gross inaccuracies, such as observed in Fig. 3.2-1b, were not present in the smoothed TSPI for LPN-15). However, differences between the simulated missile flyout and that from the smoothed range TSPI were still observed.

SIMLAB (the AIM-9 HWIL lab at China Lake, Fig 1-2) stand-alone runs were performed which used the exact LPN-15 launch conditions. The results of the missile trajectories from these runs were used to determine envelopes of bounding values. The envelopes were then compared to the actual LPN-15 data in Figures 3.2-2a and 3.2-2b. These figures show the following:

- There were variations in the missile flyouts from run to run, even when identical launch conditions and target trajectories were input to the SIMLAB on each run. The AIM-9M seeker did not respond to the inputs in exactly the same way every time. However, the run-to-run variations are relatively small resulting in narrow envelopes during the midcourse phase of the flyout.
- The "God's-eye" view (Fig. 3.2-2a) shows very good agreement between the SIMLAB results and the live test.
- The side view (Fig. 3.2-2b) shows less agreement. For a short time at the start of its flyout the SIMLAB missile flew slightly above the live missile. However, for most of its flyout, the SIMLAB missile flew significantly below the live missile and approached the target from a smaller angle relative to the horizontal direction.
  - The live missile appeared to take longer for its initial guidance correction (at the start of its flyout the AIM-9 flies without any steering in order to safely separate from the launch aircraft). This resulted in the live missile being lower than the simulated missile and having to compensate by flying a flatter trajectory to the target.
- In spite of these differences, the simulated missile responded to the target and correctly guided to it. When the AIM-9 expert examined the trajectory plots, along with the seeker telemetry data, his judgment was that the performance of the simulated missile was valid for the given scenario. Note the qualitative features in both the live and simulated missile flyouts:
  - An initial straight "safe-separation" segment.
  - A distinct guidance correction at the end of the "safe-separation" segment.
  - Continual and smooth closing on the target with no gain in missile altitude.
- Note that the simulated target was modeled to execute a perfectly flat right turn, whereas the live target's altitude varied slightly. The differences in the target trajectory were minor and did not significantly affect the missile flyout.

Conclusions from this comparison are as follows:

- The SIMLAB stand-alone simulation of the missile flyout for the LPN-15 conditions was valid. (Note that the AIM-9 Program Office has accredited the SIMLAB as a valid simulation in support of AIM-9 testing.)
- There were some minor differences in the simulated missile flyout compared to LPN-15 which reflect simulation fidelity and/or validity of the LPN-15 data.
- The LPN-15 data do not necessarily give a more accurate representation of the missile in this scenario.
  - The LPN-15 data were derived from range measurements and are subject to inaccuracies and uncertainties.
  - The LPN-15 data represent only a single realization of the missile behavior for this scenario. As the SIMLAB results show, there were run-to-run variations in the performance of the missile seeker and guidance for the exact same scenario.
- For the above reasons, the envelope of SIMLAB stand-alone results was judged to give a better standard for comparison with the linked results than did the LPN-15 data. This comparison was used to determine if linking the simulators resulted in any degradation in the SIMLAB simulation performance (the SIMLAB in the linked configuration cannot represent the missile behavior any better than in the stand-alone configuration).
- The features noted in both the live and the stand-alone simulated missile flyouts can be used for qualitative validation of the linked missile flyouts.

Pilot Replication Differences. As noted previously, another factor in preventing a direct quantitative comparison between live and linked results is that the pilots cannot be expected to perfectly replicate the live fire profiles.

During LSP testing differences in launch conditions (e.g., range, altitudes, target aspect angle) resulted in missile trajectories which did not directly overlay the LPN-15 results. In this case, qualitative validation was used by comparing the shapes of the missile trajectories.

Quantitative Validation Example. Quantitative validation was accomplished by comparing the missile flyout from linked testing to the envelope of flyouts generated by running the missile HWIL simulation in a stand-alone configuration and using the same data generated by the aircraft during the linked runs. This is illustrated by results from LFP testing.

The run from linked testing which best replicated OP-612 (Run #11) is compared to MISILAB stand-alone runs which used the same aircraft data as Run #11 in Figures 3.2-3a and 3.2-3b. Note that these figures show that the missile flyout from the linked run fell completely within the envelope of the MISILAB stand-alone runs. Further, the missile flyout from the linked run had the same general shape as the flyouts from the MISILAB stand-alone runs. Note that the missile flyouts all displayed the "single loft" shape, in contrast to the flyout from the OP-612 live fire test. This was because the targeting messages from the LFP linked run contained accurate target position and velocity data (to within the accuracy of the shooter fire control radar), and the messages from the actual OP-612 test had some inaccuracies.

4. Summary

Verification of the SIT linked testing configurations used a methodical, incremental process to establish the accuracy and timing of the data passed between the nodes during linked runs. The structured approach began with systematic check-out of each stand-alone simulator/ facility, followed by testing of each pair of linked nodes, and culminated with the check-out of the complete linked architecture. Sufficient time must be allocated in the test schedule to allow thorough exercising of the "test, analyze, fix, test" cycle before beginning formal testing. The verification approach was consistent with the bottom-up testing, functional testing, and data interface testing methods in Reference 11.

The SIT results show that validation of missile performance from linked testing must rely on a multi-step process which incorporates both qualitative and quantitative comparisons. A number of complications prevent a direct quantitative comparison between linked results and live fire data. The quantitative validation method involves first establishing the validity of the missile HWIL lab results in its stand-alone configuration and then using the stand-alone HWIL lab as a source of validation data for the linked results. The validation approach was consistent with the predictive validation and comparison testing methods in Reference 11.

5. References

NOTE: References 1 through 10 are available at the Download Area of the JADS web site:
http://www.jads.abq.com/html/jads/techpprs.htm

[1] System Integration Test, Linked Simulators Phase, Final Report, Joint Advanced Distributed Simulation Joint Test and Evaluation, Albuquerque, New Mexico, July 1997.

[2] McKee, L., "Validation of Air-to-Air Missile Performance in Advanced Distributed Simulations," Proceedings of the International Test and Evaluation Association Workshop, Oxnard, California, 21-24 July 1997.

[3] McKee, L., "Air-to-Air Missile Testing Using Advanced Distributed Simulation," Proceedings of the International Test and Evaluation Association Workshop, Oxnard, California, 21-24 July 1997.

[4] McKee, L., "Latency and Its Effects on the Fidelity of Air-to-Air Missile T&E Using Advanced Distributed Simulations," Proceedings of the 1997 Fall Simulation Interoperability Workshop, Orlando, Florida, 8-12 September 1997.

[5] Sturgeon, S. J. and McKee, L. L., System Integration Test, Live Fly Phase, Final Report, Joint Advanced Distributed Simulation Joint Test and Evaluation, Albuquerque, New Mexico, March 1998.

[6] Ayers, D. S., et al., "Linking Advanced Distributed Simulation With Flight Testing," Proceedings of the 1997 International Test and Evaluation Association Annual International Symposium, Orlando, Florida, 15-19 September 1997.

[7] McKee, L., "Air-to-Air Missile Testing By Linking Live Aircraft to a Missile Hardware-in-the-Loop Simulation," Proceedings of the International Test and Evaluation Association Workshop, Las Cruces, New Mexico, 8-11 December 1997.

[8] McKee, L., "Compensating for Latency Variations in Air-to-Air Missile T&E Using Live Aircraft Linked to a Missile HWIL Simulation," Proceedings of the 1998 Spring Simulation Interoperability Workshop, Orlando, Florida, 9-13 March 1998.

[9] Duffany, J. and Sturgeon, S. J., "Lessons Learned From Executing an ADS Air-to-Air Missile Test in Near Real-Time," Proceedings of the 1998 Spring Simulation Interoperability Workshop, Orlando, Florida, 9-13 March 1998.

[10] McKee, L., "Air-to-Air Missile T&E Using Live Aircraft Linked to a Missile HWIL Simulation," Proceedings of the International Test and Evaluation Association Workshop, Oxnard, California, 8-11 June 1998.

[11] Verification, Validation and Accreditation (VV&A) Recommended Practices Guide, Office of the Director of Defense Research and Engineering, Defense Modeling and Simulation Office, November 1996.

Author Biography

DR. LARRY MCKEE has 27 years experience directing and performing R&D programs in DT&E, nuclear weapon effects, system survivability, neutral particle beam interactive discrimination, and high energy laser effects. This experience includes 20 years as an Air Force officer with duties in management of advanced R&D programs in directed energy weapon technology, R&D leadership at the Air Force branch and division levels, development and instruction of advanced graduate courses, and technical direction of underground nuclear tests. He joined SAIC in 1989 and currently supports the JADS JT&E as the technical lead for the System Integration Test, designed to evaluate the utility of ADS for the T&E of integrated launch aircraft/missile systems.

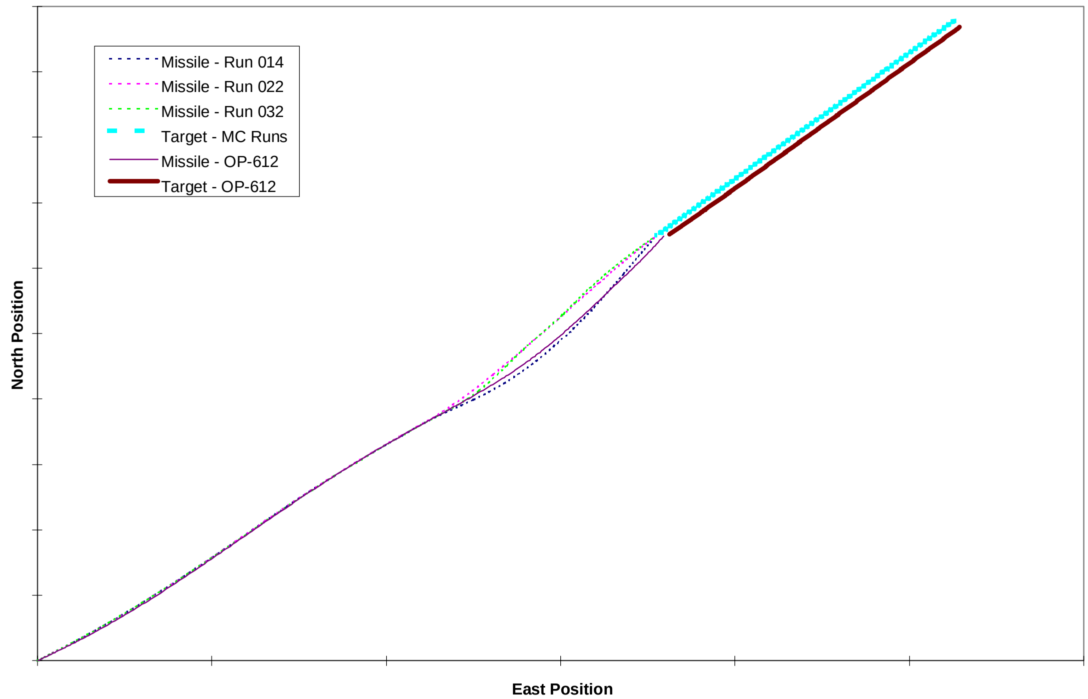


Figure 3.2-1a. Envelope of MISILAB Stand-Alone Runs (using OP-612 inputs and launch conditions) Compared to OP-612 Data - "God's-Eye" View.

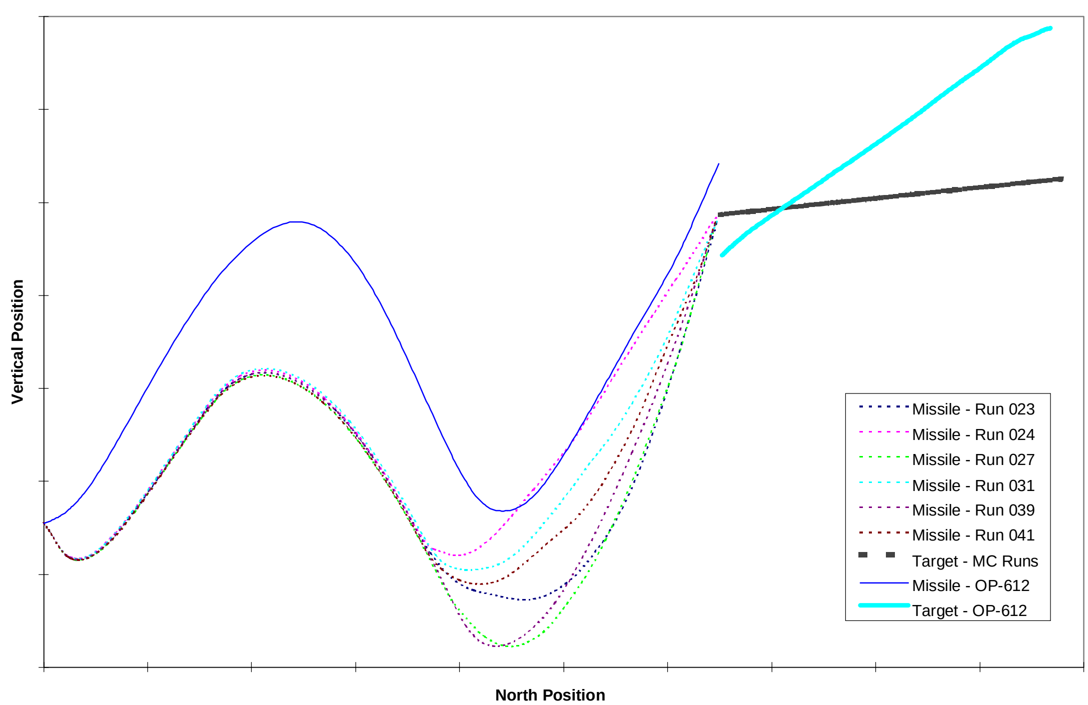


Figure 3.2-1b. Envelope of MISILAB Stand-Alone Runs (using OP-612 inputs and launch conditions) Compared to OP-612 Data - Side View.

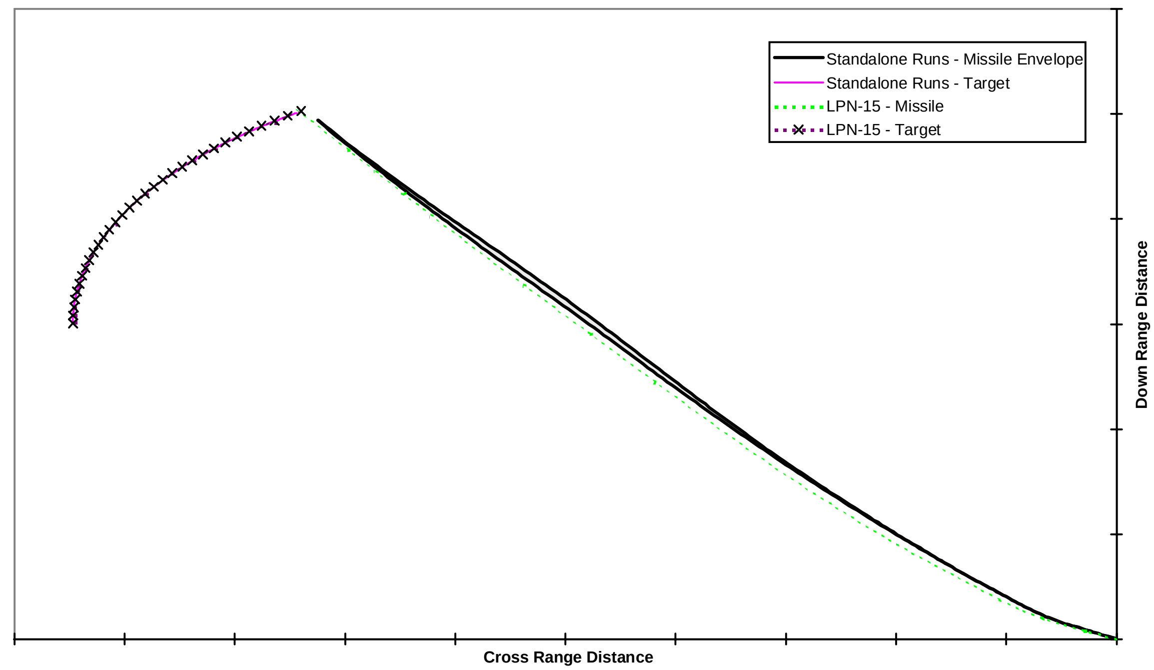


Figure 3.2-2a. Envelope of SIMLAB Stand-Alone Runs (using exact LPN-15 launch conditions) Compared to LPN-15 Data - "God's-Eye" View

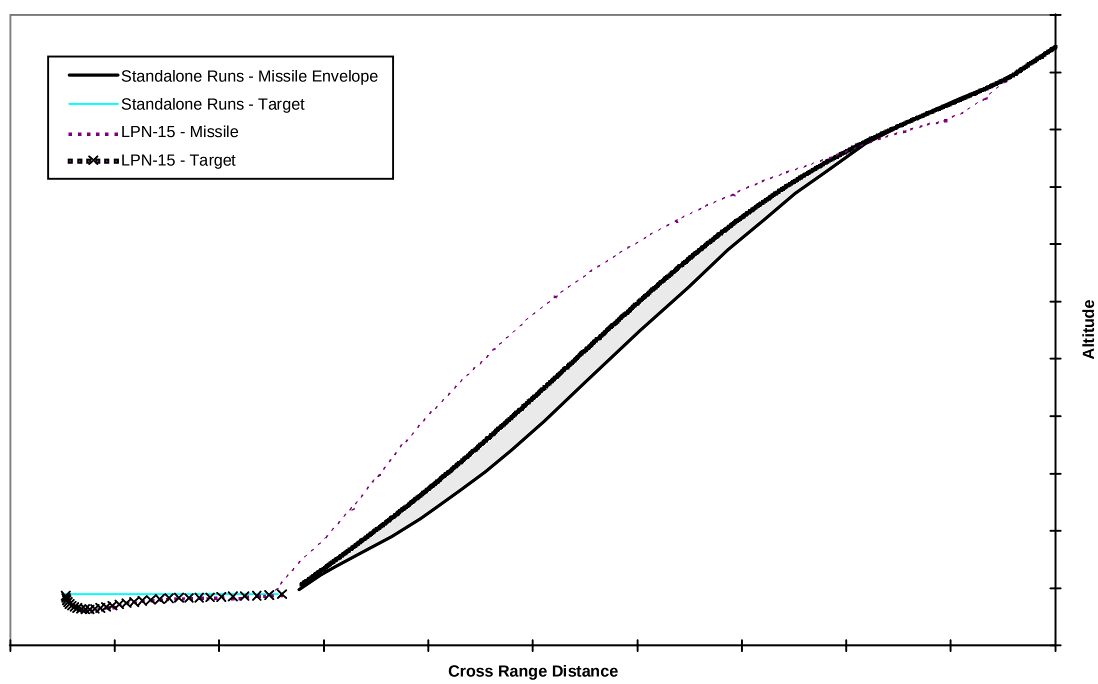


Figure 3.2-2b. Envelope of SIMLAB Stand-Alone Runs (using exact LPN-15 launch conditions) Compared to LPN-15 Data - Side View

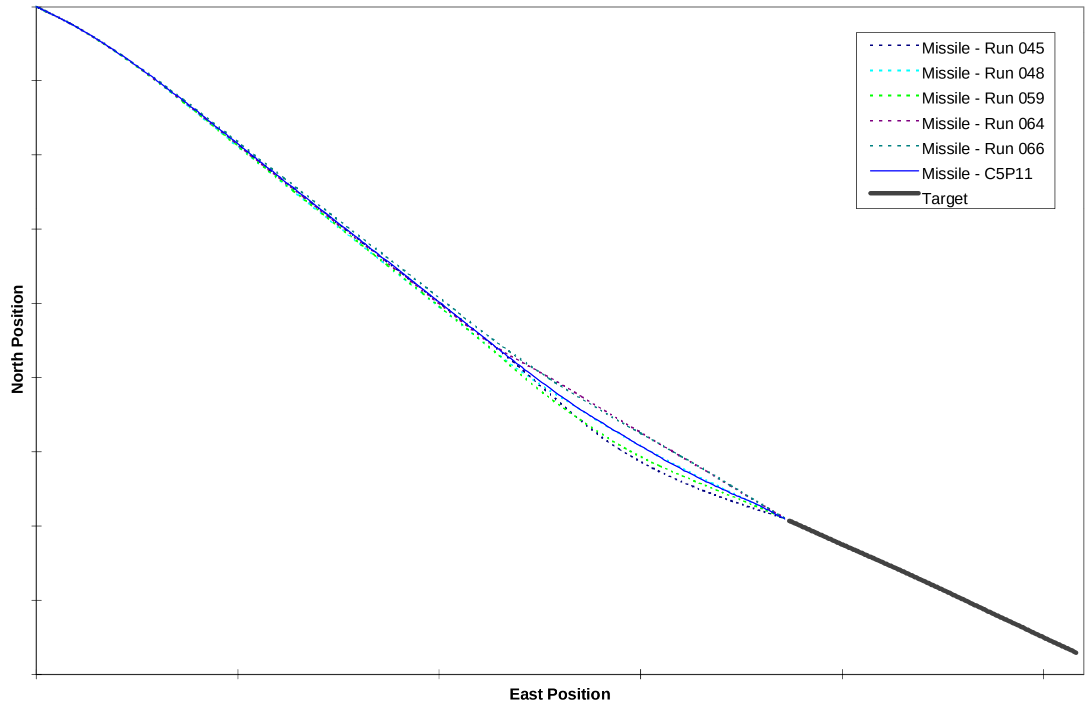


Figure 3.2-3a. Missile Flyout for Selected OP-612/TWS Profile (Run #11 - 11 Sep 97) Compared to MISILAB Stand-Alone Runs (using Run #11 conditions) - "God's-Eye" View.

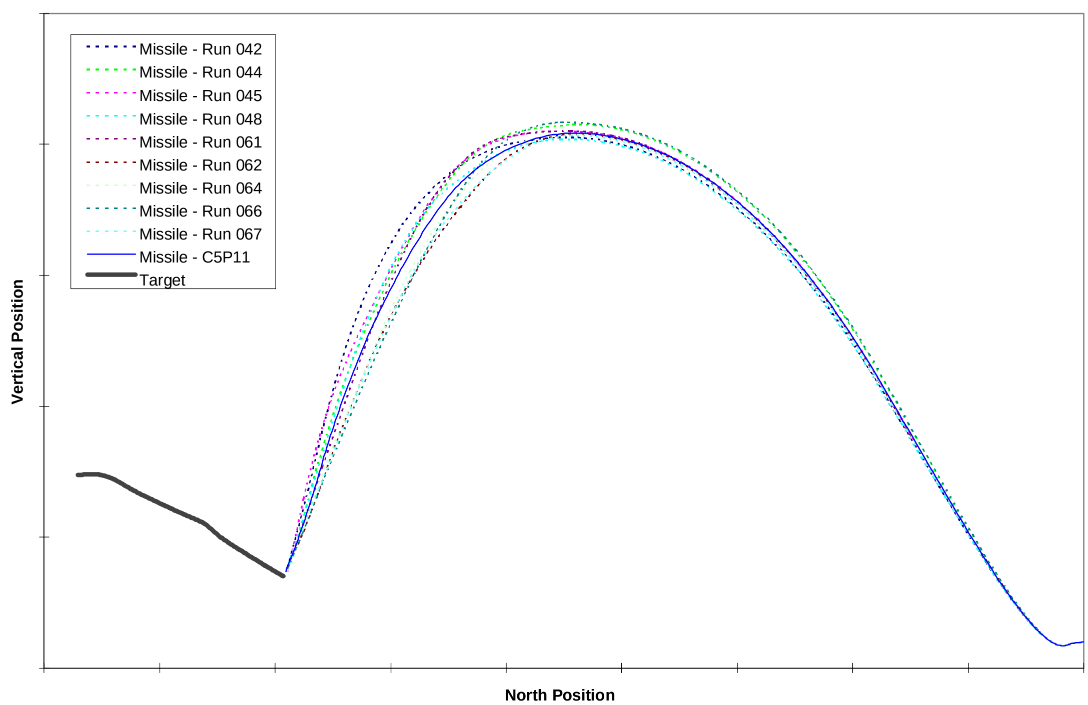


Figure 3.2-3b. Missile Flyout for Selected OP-612/TWS Profile (Run #11 - 11 Sep 97) Compared to MISILAB Stand-Alone Runs (using Run #11 conditions) - Side View.